IO: HEAT FLOW AND SURFACE AGES.

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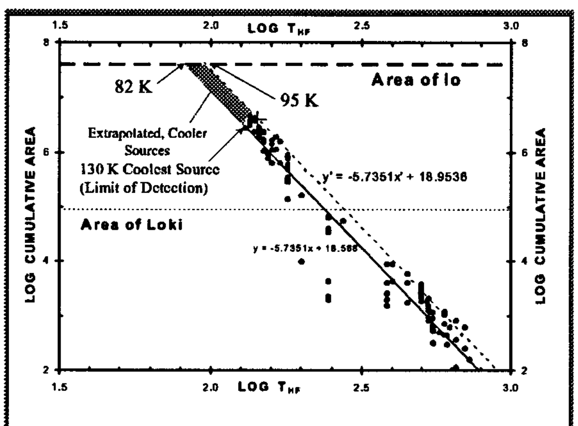
Introduction: Io is the most volcanically active body known. It has the highest heat flow observed for any solid planetary body. Knowledge of Io's heat flow is important because its value constrains models for 1) Io's interior, 2) the rate of evolution of Io's orbit, and 3) Jupiter's interior. The emerging heat is believed to originate in the interior, arising as a product of tidal dissipation. It is brought to the surface by eruption of lava and then radiated to space. For the past twenty years, observations of this radiation have been used to determine lower bounds for the heat flow [1-9]. The values for these range from 1 to 3 Wm^{-2}. An unexpected outcome from the techniques developed for studying Io's heat flow are specific predictions for the minimum temperatures of lava flows. These have now been confirmed by observation. Thus, the modeling of the temperature of cooling lava provides a method for dating Io's surfaces.

Upper Bound on Heat Flow: Recently, an upper bound has become available for Io [10]. That



value is 13 Wm^{-2}, about a factor of six higher than the midpoint of the range of the lower bounds. The upper bound was obtained through an analysis of the thermal anomaly data of Veeder *et al.* (1994), see Figure. A curve representative of an upper envelope for the range of the data was extrapolated until it intersected the surface area of Io. The heat flow corresponding to this curve is 13 Wm^{-2}. This extrapolation allows for cooler sources which are not observed because they are below the detection limit of the technique used. On the other hand, the heat flow obtained is too large because: 1) the curve used is in itself an upper envelope, 2) some areas on Io's surface (e.g., mountains) may not be covered by lava flows and hence are not part of the extrapolated anomaly population. The surface area of Io provides the termination for the extrapolation. This implies that lava flows cooler than ~90-95 K have been on the surface long enough to be covered by newer flows.

"Minimum" Nighttime Temperature: Direct observations of nighttime temperatures by the Galileo PPR instrument have been reported by Spencer [8]. In all observed regions, away from the sunset terminator and away from obvious thermal anomalies, the minimum temperatures are everywhere about ~93 K. The profoundness of this observation lies in the fact that these minimum temperatures are independent of latitude and time since sunset. This unique property of the global temperature distribution has been cited as evidence that these surface temperatures are not controlled by absorbed sunlight [10, 11]. Matson *et al.* have suggested that these are in fact the volcanically controlled temperatures as predicted by extrapolation from the known thermal anomalies [10, 11] (see figure to the left). This hypothesis offers a simple and direct explanation of the observed spatial distribution of the "minimum" temperatures. The conclusion that follows is that almost the entire surface of Io is covered by cooling lava flows.

Cooling of Lava Flows: The solidification and cooling of lava on the surface of Io has been modeled by a number of workers [12,13,14]. For example, the Davies model [13] generates a distribution of temperatures and areas that is a function of the age and areal extent of the lava body, where the surface temperature is a function of the thickness of the crust that has formed on the surface of the flow. Heat loss is buffered by the release of latent heat. Generally, cooling models of this type initially assume liquid semi-infinite half spaces losing heat from the surface by radiation. These models are valid for as long as the flow remains liquid. Recent Galileo observations of Io and analyses of data have led to determination of lava flow thicknesses that range from ~1 to 10 m [15,16]. To date, no thicker flows have been identified, nor have any structures indicative of high-viscosity lavas: flows on Io, high-temperature and low viscosity, may all be relatively thin. A 10-m thick ultramafic flow will solidify in about a year [17], assuming crusts form both at the base and top of the flow. To study the temperature distribution on the surface of Io and derive the ages of different units as a function of temperature, subsequent post-solidification cooling trends have to be followed. We do this using a finite-difference radiative transfer model. We find that after solidification, cooling is rapid compared to thicker bodies where latent heat is still being released. Using the extended model, the 10 m thick flow will reach a surface temperature of 90 K in about 130 years. A thinner flow cools faster. At the other end of the timescale a ~600 m thick flow takes the order of 10^4 years to reach 90 K.

The model is being refined to account for changes in albedo as different condensates successively form on the flow surface as temperature decreases: first sulfur, then sulfur dioxide. The different thermal properties of these additional layers will affect but will not stop the heat flow and resulting thermal emission. The physics of thermal emission and flow emplacement and solidification are well understood. The limitations of application and source of subsequent errors are due to the uncertainties in model input parameters. Better determination of these parameters is perhaps the most fruitful task that can be undertaken in order to understand Io's volcanic processes and the ages of its surface units.

Thermal Chronology: The very young geologic age of Io's surface does not permit dating and stratigraphy using crater counts. However, since the resurfacing is due to Io's recurring and widespread volcanism, the remote sensing of temperatures enables the use of both relative and absolute thermochronometry to determine surface ages (*e.g.*, [15], [16]).

Individual lava flows cool with time and the surface temperature of a particular lava flow is related to it's age, thickness, and composition. Galileo continues to provide new data on Io's lava flow composition and thickness as well as nighttime surface temperatures.

We have suggested the possibility that the entire surface of Io (excepting only the mountain peaks) is a global volcanic field. Thus, any recognized geologic unit on Io can be assigned a relative age even in the total absence of craters. Of course, it is most straightforward to begin by comparing the relative ages of different volcanic calderas, flows, and plains. In addition, the minimum apparent nighttime temperature observed near the poles of Io [8] (between obvious active centers) suggests a corresponding maximum age (*cf.*, [15], [16]).

The best estimates for a lower bound on Io's heat flow remain well above current steady state tidal models for the production and the transport of magma to the surface, *e.g.* [6], [8], [9], [10], [11]. The upper bound [10], [11], highlights this problem. One refuge is an appeal to a current "special time" period of extremely high volcanic activity or other *ad hoc* cyclic variations. A relative ordering of the style, distribution, and magnitude of volcanism on Io using temperatures to "date" surfaces provides a new way to address these unanswered questions.

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